# Philippine Geoid Model 2018

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Running title: Refinement of the Philippine Geoid
Key Points of this manuscript:

1. Computation of the preliminary Philippine Geoid
2. Re-computation of the geoid
3. Computation of the 2018 geoid using new satellite and land data

**Abstract.** This paper discusses the computation and re-computations of the preliminary Philippine Geoid Model 2014 (PGM2014) into PGM2016 and then PGM2018 with the technical assistance of the National Space Institute, Technical University of Denmark (DTU-Space) using data from land gravity, airborne gravity, marine satellite altimetry and the satellite gravity data from the GOCE. Digital terrain models used in the computation process was based on 15" SRTM data. The preliminary hybrid model is computed in a global vertical reference system with a Standard Deviation of 0.25 m, then fitted to the GNSS/Leveling with an RMS value of 0.50 m at that point in time, highlighting the challenges in the geodetic infrastructure of the Philippines, with extreme gravity field variations and geodynamics. To improve the PGM2014, it was re-computed to PGM2016 using the reprocessed, re-analyzed and densified land gravity and GNSS/Leveling data. Significant improvement was seen in the reprocessed gravity data as well as the final geoid (SD=0.022 m; RMS = 0.054 m). In 2018, with new satellite data available, densified gravity data, and additional GNSS/Leveling points were used in a new geoid computation. The new computed geoid has an improved fit to GNSS/Leveling of 2 cm. The formal error estimate of the new geoid across the Philippines is around 10 cm rms. Further densification of the land gravity in towns and cities to 41,000 points will be conducted from 2019 until 2030 to further refine the geoid. Re-computation will be done for the new version of the geoid as new gravity data comes in.

Keywords: Air-land Bouguer differences, Geoid correction surface, RMS fit to GNSS/Leveling

## 1. Introduction

In almost all projects of building "something" on the surface of the earth, there is a need to determine where the water will flow for the design of water supply and drainage systems. Therefore, elevation information of the area is a requirement of every project. This elevation information would require the determination of elevation of points on the ground. The conventional way of determining elevation of points is through the conduct of geodetic leveling, which is very tedious and time consuming. With the advent of GNSS, it has become possible to estimate mean sea level (MSL) elevation of points using the formula

$$H = h - N \quad (1)$$

where H is the MSL height, h is the ellipsoidal height from GNSS survey, and N is the geoid height

The geoid height requirement can be supplied by a geoid model computed from gravity data while h can be obtained by GNSS. Using a geoid model together with GNSS will save time and money with projects that does not need very high elevation accuracy. Computing a geoid model for the country has always been the aspiration of the Geodesy Division of the National Mapping and Resource Information Authority (NAMRIA). This paper will briefly describe the computation of the first Philippine Geoid Model (PGM), its airborne gravity survey, land gravity data and the geoid nominal accuracies. The third part will talk about the re-computation and improvement of the preliminary geoid into PGM 2016. Section 4 will discuss the new satellite gravity data, additional land gravity and GNSS/Levelling data used in the new 2018 computation. All computations include quality control plots of the land gravity and GNSS/leveling fit.

## 2. The preliminary PGM 2014

In 2014, the National Space Institute of the Denmark Technical University (DTU-Space) conducted a nationwide airborne gravity survey (Olesen, 2014) funded by the National Geospatial Intelligence Agency (NGA) to improve the global gravity field model EGM2008. The mean altitude for all flights was 3,185 m with a terrain clearance of 545 m above mountains and 3760 m in lowlands as shown in the flight track. The estimated rms error of the airborne data is 2.6 mGal, based on cross-over error analysis; since tracks were flown at non-constant heights (Figure 1), the real accuracy might be better.

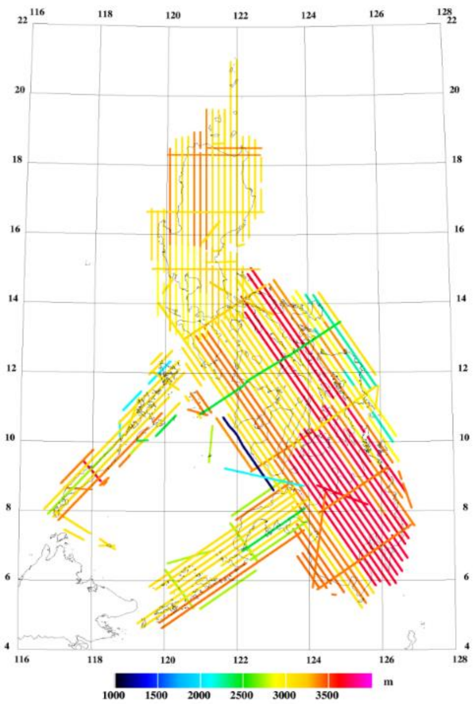


*Figure 1. Color-coded flight track elevations of the DTU/NGA/NAMRIA airborne gravity survey, 2014.*

Following the airborne gravity survey, the NAMRIA has computed a preliminary hybrid geoid model - Philippine Geoid Model 2014 (PGM2014) with the assistance of Professor Rene Forsberg. PGM2014 used datasets from 1,261 land gravity surveys, airborne gravity survey, marine satellite altimetry (DTU-10), and the newest satellite gravity data from the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission release 5. The geoid was computed using RTM terrain reductions, and a rigorous downward continuation process by least-squares collocation using the GRAVSOFT system, a set of Fortran routines developed through many years of research and project work at DTU-Space and Niels Bohr Institute, University of Copenhagen (Tscherning, Forsberg, & Knudsen, 1992). The details of the method is described in detail in (Forsberg, Olesen, Gatchalian, & Ortiz, 2014). Comparison of airborne and land gravity data after terrain and EGM reduction were done for quality control. Large errors in the land gravity data were discovered (air-land differences of >50 mGal) and is shown in Figure 2. The final geoid "restore" statistics and standard deviation of the reduced geoid is listed in Table 1.

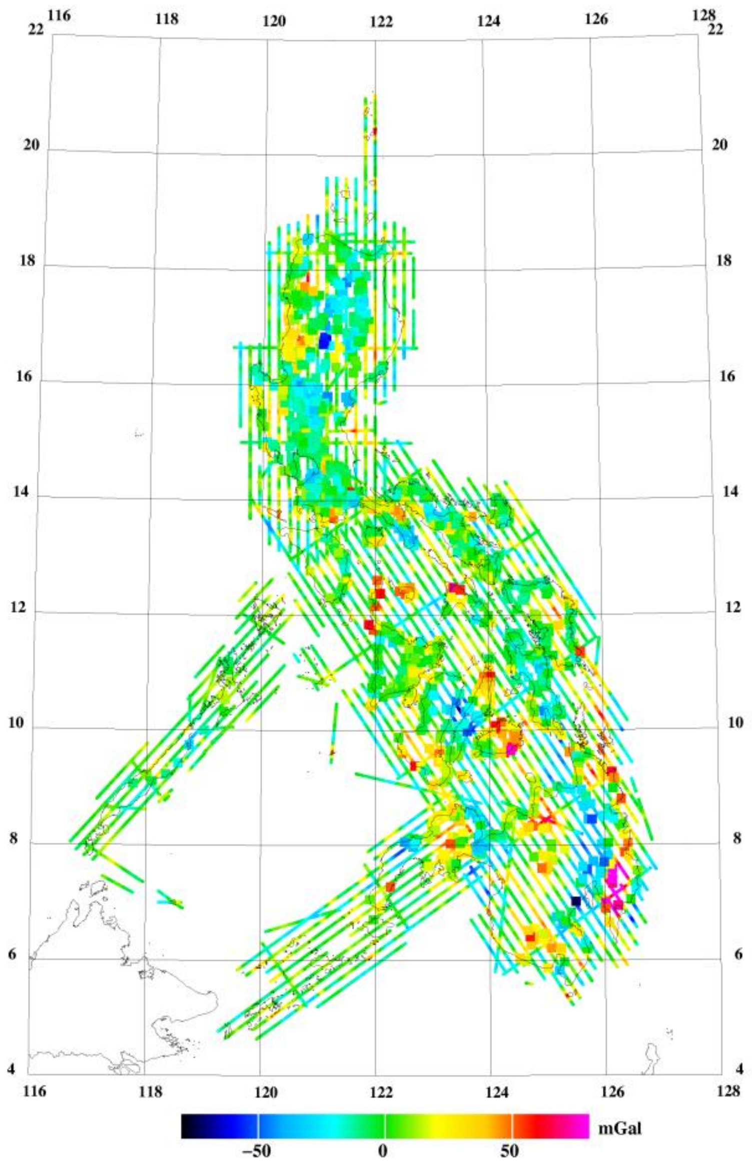


*Figure 2. Outliers of the quality check between land and airborne gravity data (magenta and dark blue dots)*

| Unit: meters | Mean | Std.dev. | Min. | Max. |
|---|---|---|---|---|
| Reduced geoid (after spherical FFT) | 0.00 | 0.25 | -1.61 | 2.88 |
| RTM restore effects (computed by FFT) | 0.00 | 0.04 | -0.23 | 0.74 |
| Final gravimetric geoid statistics | 39.06 | 18.36 | -9.02 | 76.43 |

Table 1.Computed geoid statistics and standard deviation of PGM2014

For a hybrid or MSL-based geoid, a set of 190 GNSS data in ITRF2005 levelling benchmarks was made to fit the gravimetric geoid. This is done by "forcing" the geoid heights ($N_{geoid}$) to coincide with the observed geoid heights of GNSS/levelling ($N_{h-H}$), thus preserving the existing vertical datum of the country, i.e., MSL. In this fitting, these GNSS data showed a relatively large error relative to the geoid, with large outliers in some regions, likely due to a combination of geodynamic effects and levelling or GNSS errors, as well as the separate tide-gauge defined height systems on different islands.

The rms fit of GNSS levelling is 0.5 m with maximum offset value of 1.49 m; it is therefore not possible to use these data for validation of the geoid. Figure 3 shows the offset values, and the geoid correction surface for a fitted geoid (corrector surface gridded with 80 km correlation length, and GNSS-Levelling apriori error of 10 cm). Figure 4 shows the comparison of PGM2014 (gravimetric) to EGM2008; large improvements are seen, especially in the south.

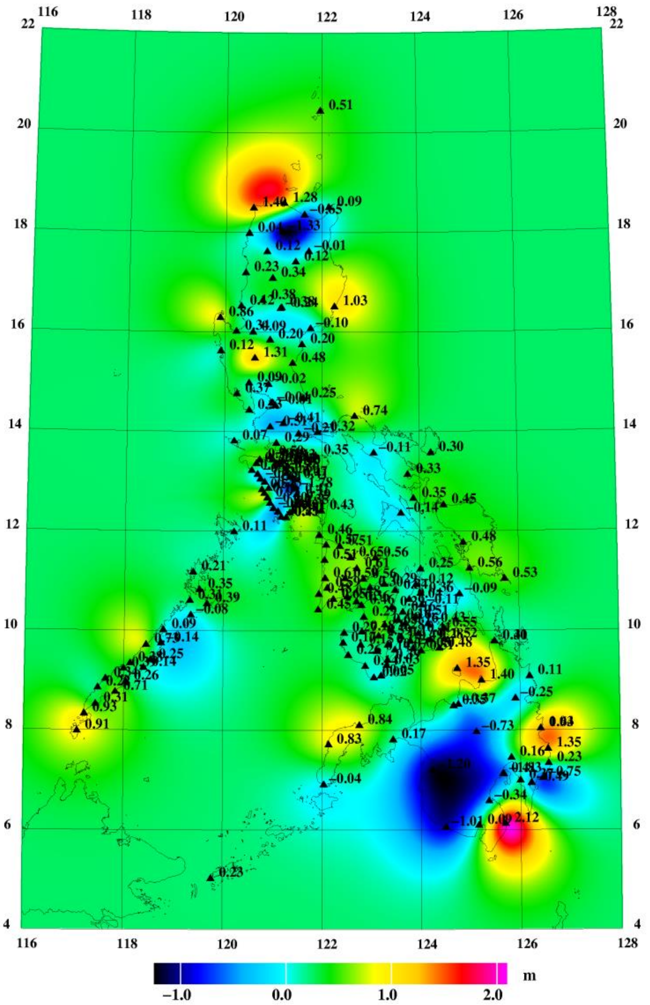


Figure 3. Location of GNSS/Leveling data in PGM2014. Color shows the offset values of the fitted geoid, after a gridding by least-squares collocation/Kriging.

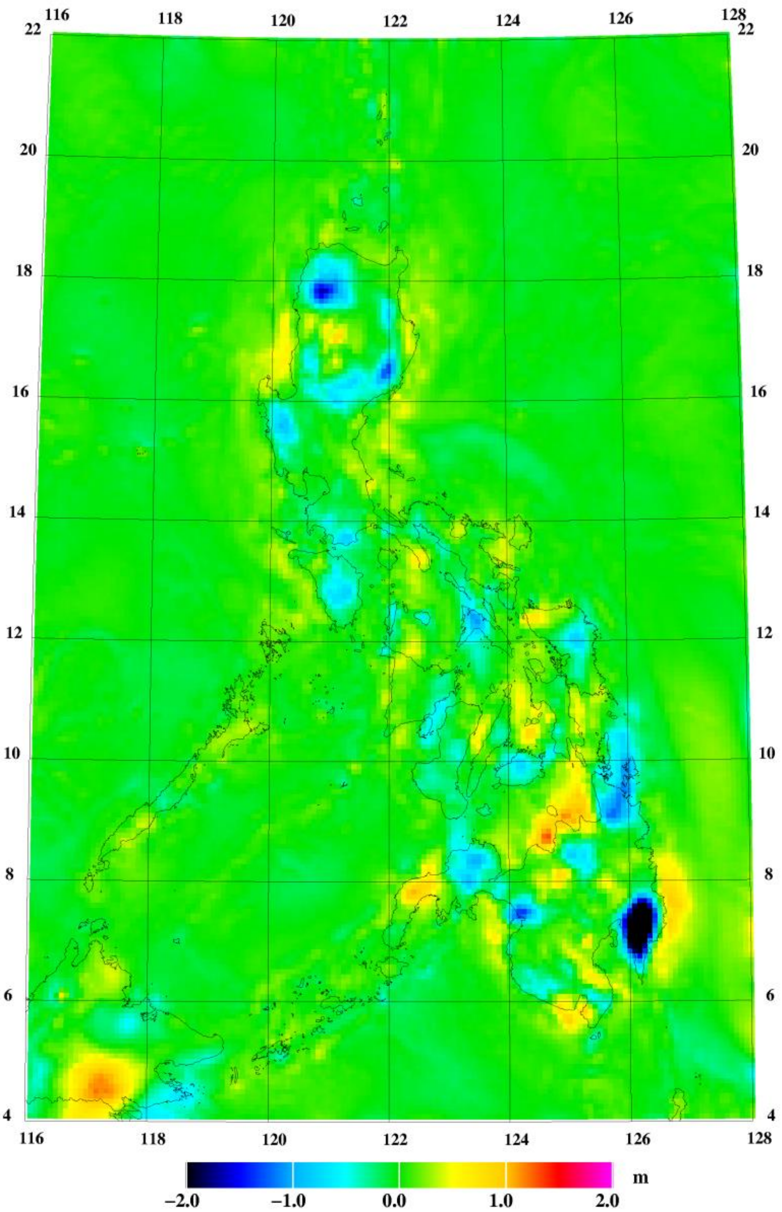


*Figure 4. Differences between geoid heights in the PGM and EGM2008*

## 3. 2016 Re-computation of the geoid

With large errors in land gravity and GNSS/Levelling data, i.e., a geoid accuracy of 0.25 m and RMS fit of 0.50 m respectively, this geoid will not satisfy most GNSS surveys requiring accuracies of 10 cm or better. Although the PGM2014 can be used in topographic surveys in remote areas where a rough elevation estimate of less than 1 m will suffice, this geoid can still and should be improved. Naturally, all surveyors would want a geoid model that can produce elevations that are a little less accurate than levelling, say < 10 cm standard deviation at 95% confidence level. To further improve a geoid model, we followed common geodetic advice, as outlined in the paper "Towards a cm-geoid in Malaysia" (Forsberg, 2005):

- *Levelling networks must be carefully analysed for adjustment errors;*
- *Connections and antenna height errors of GPS data on benchmarks must also be revisited and re-analysed;*
- *Erroneous points (geoid outliers) must be resurveyed by Levelling and GPS;*

- *New GPS-fitted version of the geoid must be computed as new batches of GPS-Levelling data, additional gravity surveys in major cities and GPS user's height problem reports comes in.*

In 2015, with the help of Professor Forsberg, NAMRIA started the re-computation of the PGM2014 (Gatchalian, 2016). In this re-computation, the 2014 satellite and airborne data processing results were used, only the land gravity, GNSS and Levelling data were reprocessed and re-analysed.

## Land Gravity 2016

The 1,261 land gravity data was reviewed and reprocessed. Errors in position of the land gravity data "outliers" in the 2014 computation were discovered, corrected and reprocessed. Densification of land gravity stations was also conducted in some major cities of the country, totalling the number to 2,214 points. One quality check of the land gravity data is the comparison of its anomalies with that of the airborne, see Figure 5. Significant improvements can be seen in the land data. Most dots are in green, some yellows and light blue (25-50 mGal difference in mountainous areas only). This highlights the need for careful QC of terrestrial gravity anomaly data, and how new airborne data can help to find systematic errors in older data.

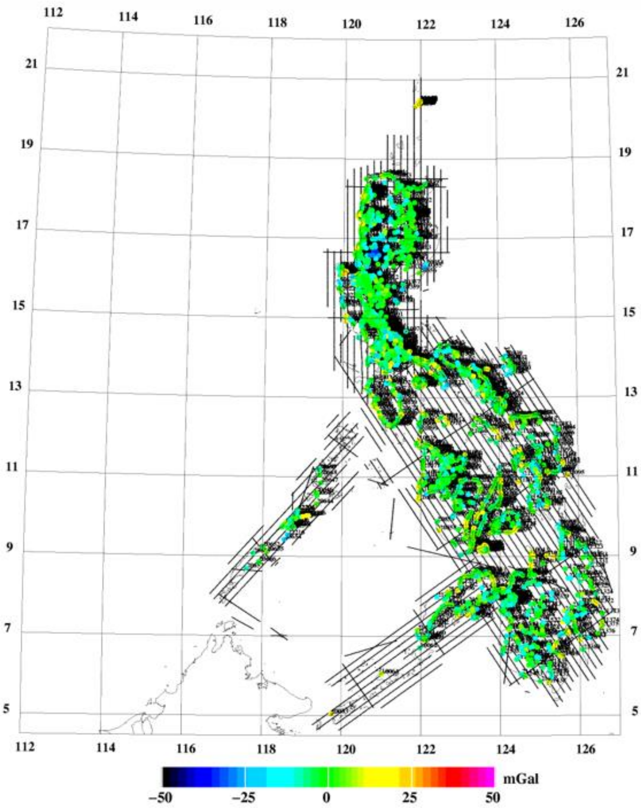


*Figure 5. PGM2016 land gravity data after reprocessing, plotted as difference to airborne data. Most differences are below 25mGals, some points exceed 35mGals in mountainous regions, which is ok given the inherent filtering of airborne data.*

## GNSS/Levelling Data 2016 and PGM2016

The 2016 levelling data was re-analysed, readjusted and corrected, with some outliers deleted. The GNSS data was reprocessed and readjusted, points with large height error and ellipses were deleted. After removing the GNSS/Levelling outliers, 101 out of the 190 BMs remain and used in fitting to the re-computed gravimetric geoid. After fitting the new GNSS/Levelling, the RMS fit is now 0.054 m with a minimum and maximum offset value of -0.124 m and 0.169 m respectively. This improvement is mainly due to the removal of erroneous levelling and GNSS points. Figure 6 shows the offset values and the new geoid correction surface of PGM2016.

The PGM2014 was re-computed to PGM2016 after the GNSS/levelling fit, with an aposteriori error of 0.022 m. This represented a major improvement in the geoid for GNSS use, and again highlight the need for careful QC of all data. Only the uniform-quality airborne data were left unchanged for PGM2016.

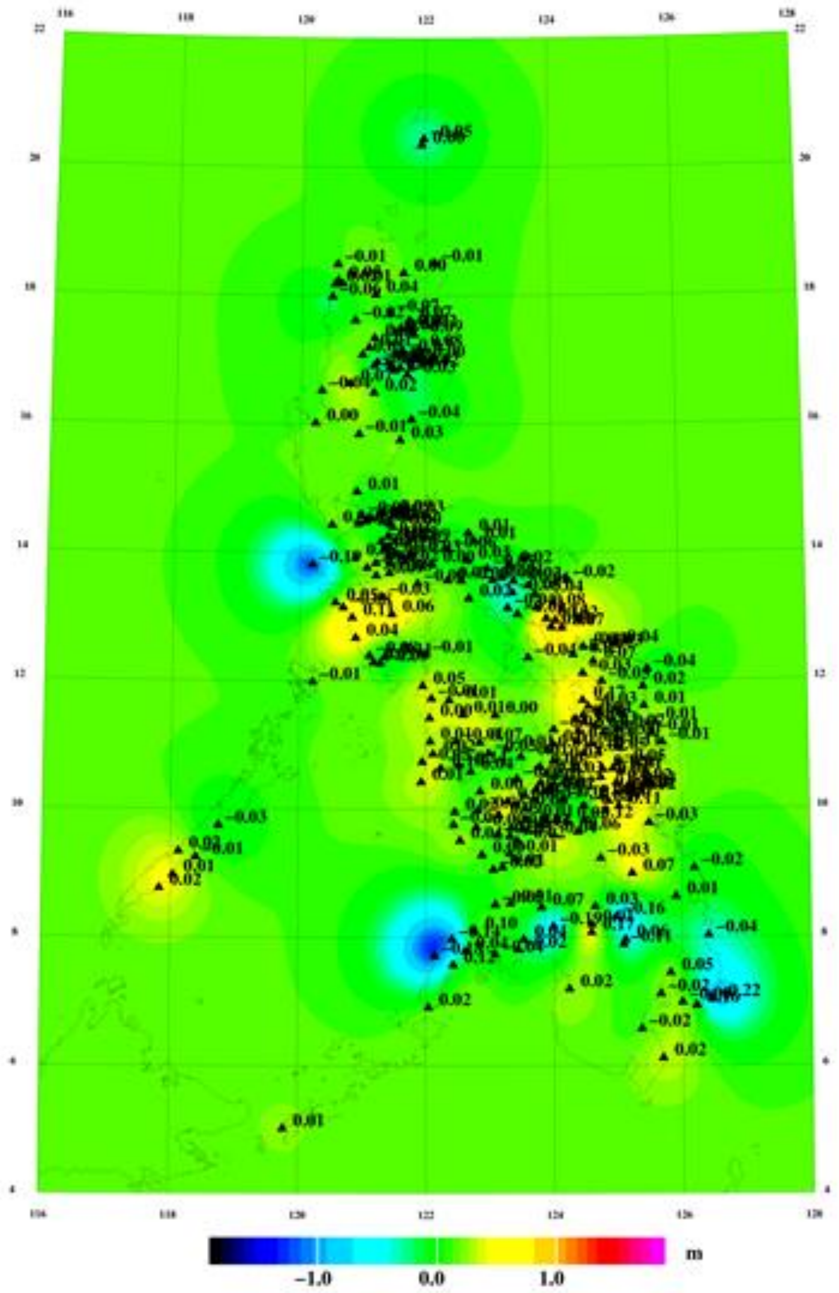


*Figure 6. New offset values of the fitted PGM2016. A few outliers are still seen, but source of these difficult to assess.*

## 4. 2018 Computation of the geoid

In 2018, with the availability of new satellite data, the Philippine geoid model was recomputed again with the original airborne, additional land gravity and GNSS/Levelling data using the *GRAVSOFT* programs. A new global model PGM2017 (Preliminary Gravitational Model 2017, a precursor of the new EGM2020 model) and updated DTU15 satellite data were used in this re-computation. The shift to the reference model PGM2017 was important, as this model contains also the airborne Phillipines data from 2014.

### Land Gravity Data

5779 land gravity data points were gathered, processed and tabulated in excel format: ID, Long, Lat, Gravity Value, Elevation - as required by the *anomaly job* program. Figure 7 shows the distribution of the densified land gravity data in the form of bouguer anomaly plot. The color-coded dots seem to conform to each other, indicating that the gravity data are in their correct positions. For quality checking, the air-land Bouguer differences ranges from 0.016 mGal to 23.4 mGal indicating the closeness of land gravity point positions to airborne data as shown in figure 8. More land gravity data, up to 41,000 will be added from 2019 until 2030 in order to further refine and re-compute a new version and the Philippine geoid.

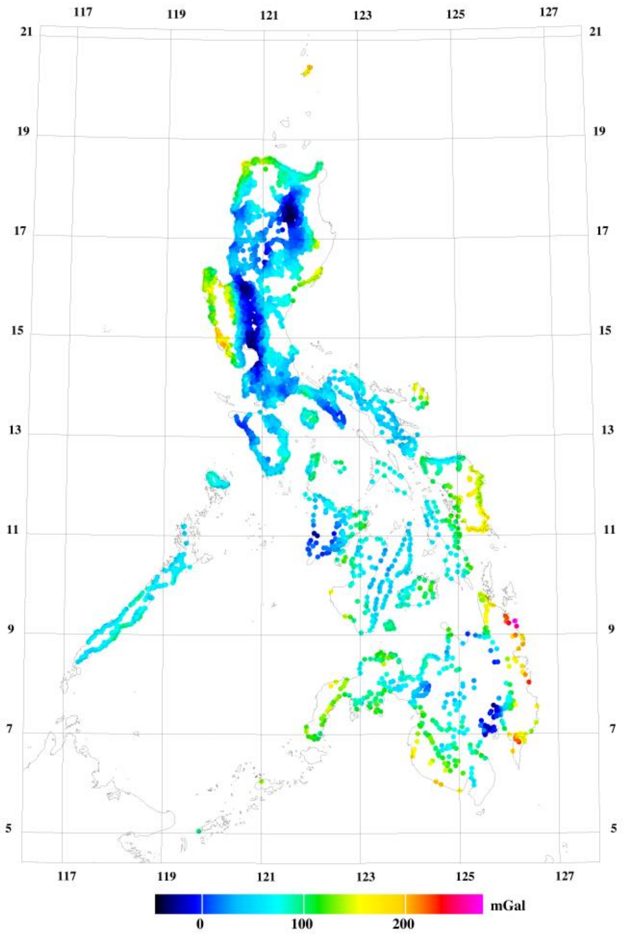


*Figure 7. Distribution of land gravity points used in PGM2018*

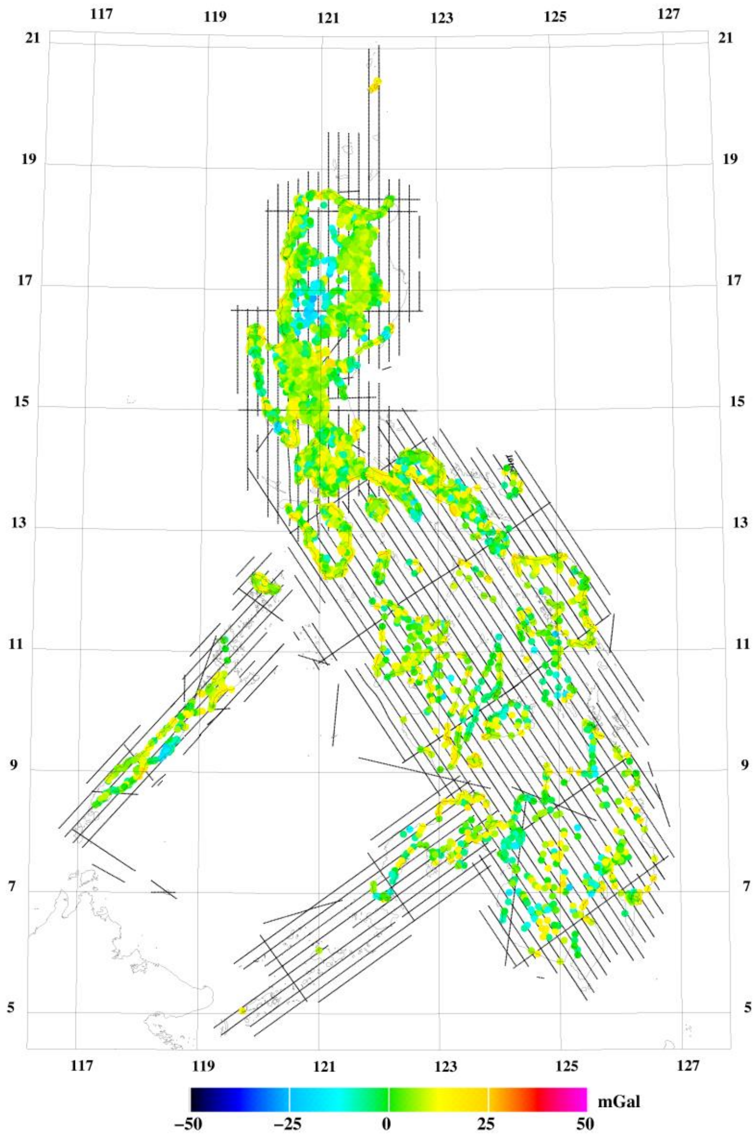


*Figure 8. Differences between airborne and land anomalies for the PGM2018 geoid.*

## GNSS/Levelling Data

A set of 286 GNSS/Levelling data were used in fitting the PGM2018 geoid - some coming from the 2016 data (101pts) then supplemented by new GNSS surveys. Figure 9 shows the distribution of Benchmarks (BMs) surveyed by GNSS. The survey was done from 2010 until 2018 with the additional points coming from the PGM Validation project that started in 2016. The GNSS survey observation time range from 2 hrs to 6 hrs depending on the length of the baseline. Height errors after adjustment range from 0.013 m to 0.094 m while error ellipses are less than 0.05 m.

The levelling data points came from the adjusted First Order Level networks nationwide with 1.96-sigma standard deviations (SD) at 95% confidence limit of the BMs ranging from 0.005 m to 0.05 m. The BMs were selected according to their location (with clear view of the sky) for the consideration of the GNSS survey requirements. GNSS/Levelling data format is: ID, Lat, Long, Elevation,$N_{h-H}$ , for use of the *fitgeoid job* program.

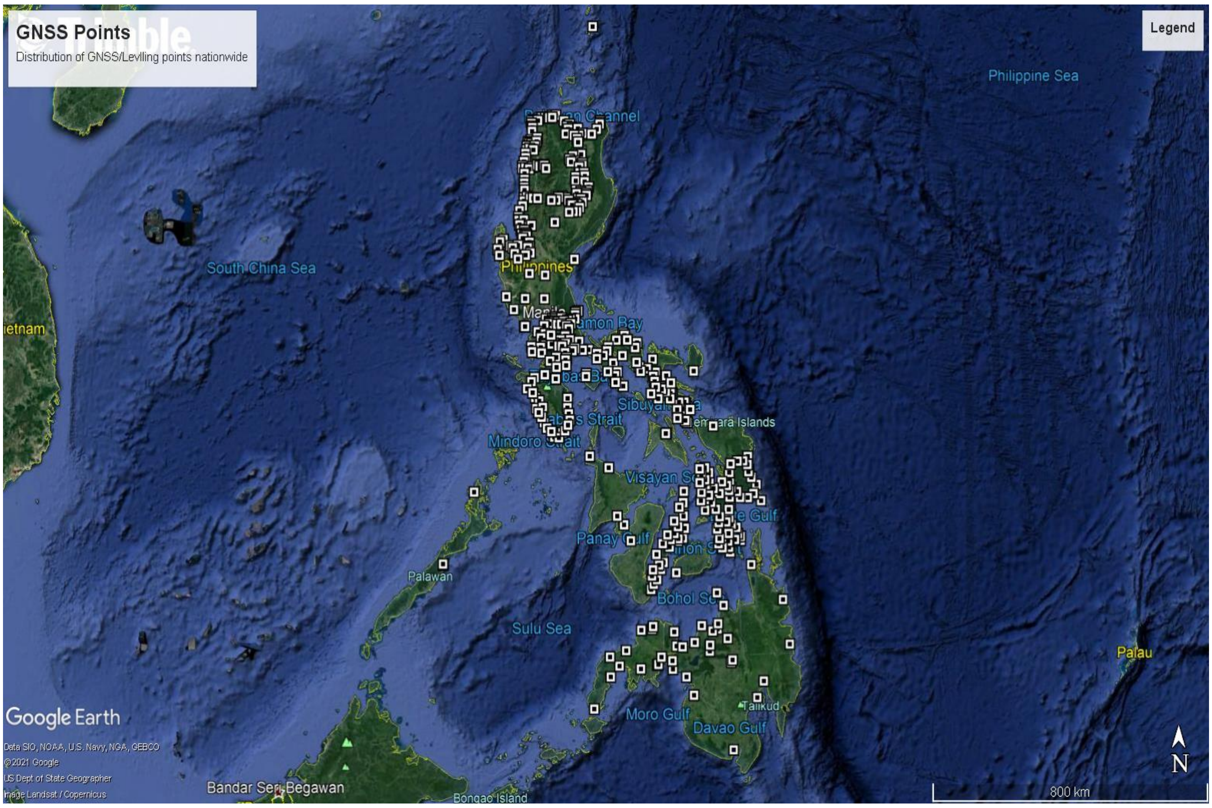

*Figure 9. The GNSS surveyed BMs as of 2018*

The RMS value of the geoid fit is 0.022 m with minimum and maximum offset values of -0.058 and 0.063m respectively, see Table 2. Figure 10 shows the post-fit offset values, and the geoid correction surface for a fitted geoid (corrector surface gridded with 60 km correlation length, and GNSS-Levelling apriori error of 10 cm). More points will be added to the GNSS/Levelling data as the PGM Validation Survey progresses.

| Unit: Meters | Mean | Std. dev. | Min | Max |
|---|---|---|---|---|
| Before Fit | 1.653 | 0.531 | 0.422 | 2.737 |
| After Fit | 0.001 | 0.022 | -0.58 | 0.63 |

*Table 2. Fitting statistics before and after fitgeoid job program*

It should be noted that in the fitting process the post-fit accuracy is very dependent on the a priori SD assumptions of GNSS and levelling accuracy, as well as the correlation length of the fit. To judge the accuracy of the underlying pre-fit gravimetric geoid accuracy, Fig. 11 shows the error estimates of the predicted geoid, with only one GNSS point – the PMSL fundamental tide gauge in Manila – fixed. Because of the memory restrictions of a single collocation error estimation run, all data have been selected only at 0.1° resolution (0.2° for DTU15). The data shows that the gravimetric geoid has an accuracy of around 10 cm across most of the Philippines territory; it should be noted, though, that the gravimetric geoid is in a global reference system, and not fitted across the various height datums on the islands.

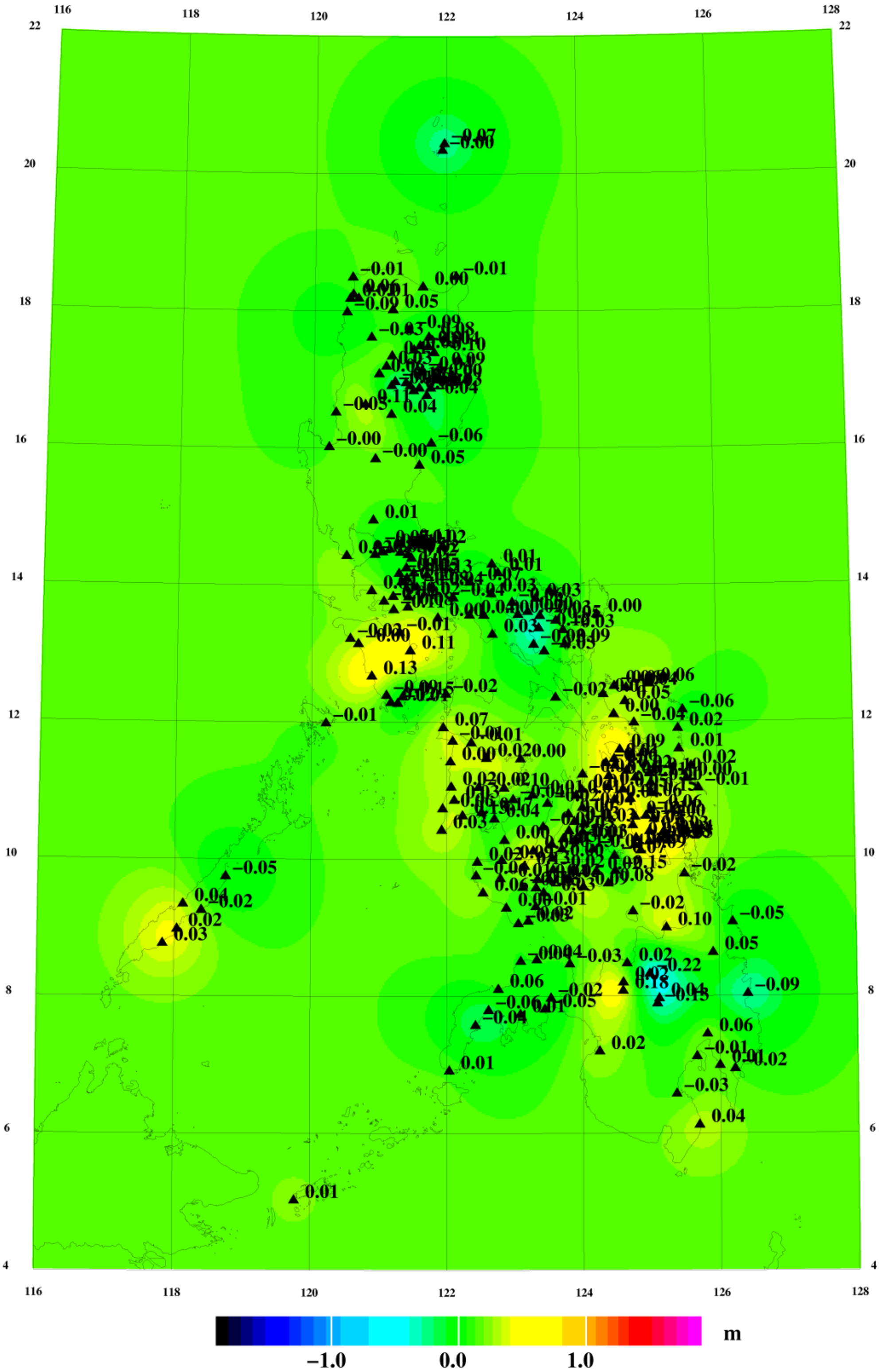


*Figure 10. PGM2018 GNSS/Levelling offset values. Most points are colored green and yellow indicating a better fit of the geoid to the BMs*

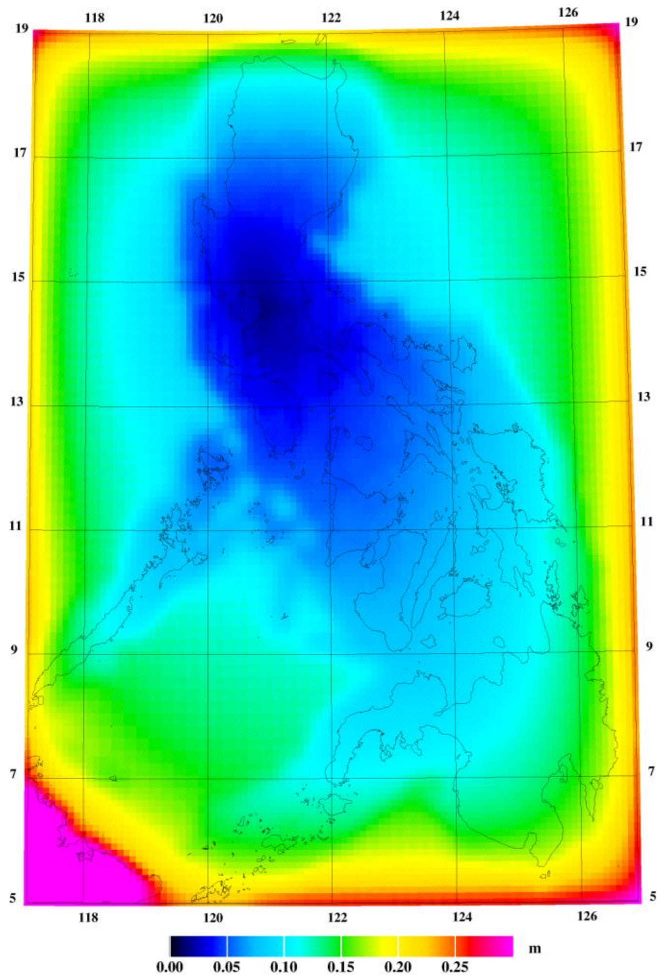


*Figure 11. Errors of the underlying gravimetric geoid, relative to the Manila reference tide gauge. Errors only computed assuming data in the shown region, with a covariance model fitted to the actual data thinned to 0.1 ° resolution.*

### The Philippine Geoid 2018

Repeating the steps enumerated in the PGM2014 computation, the Philippine geoid has been computed using PGM2017, DTU15, airborne and land gravity data. The accuracy is now 0.01 m as listed in table 3, and the underlying gravimetric geoid better than 10 cm.

Figure 12 shows the new PGM2018. The geoid model file (in GRAVSOFT *.gri*, Trimble *.ggf*, or *geotiff* formats), along with user-friendly interpolation software, is available for download at the NAMRIA website, [www.namria.gov.ph.](http://www.namria.gov.ph)

| Unit: Meters | Mean | Std. dev. | Min | Max |
|---|---|---|---|---|
| Reduced geoid | 0.00 | 0.01 | -0.16 | 0.44 |
| RTM restore effects | 0.00 | 0.25 | -1.67 | 3.13 |
| Final gravimetric geoid | 38.95 | 18.36 | -9.14 | 76.32 |

*Table 2. Statistics of PGM2018 and its Standard Deviation*

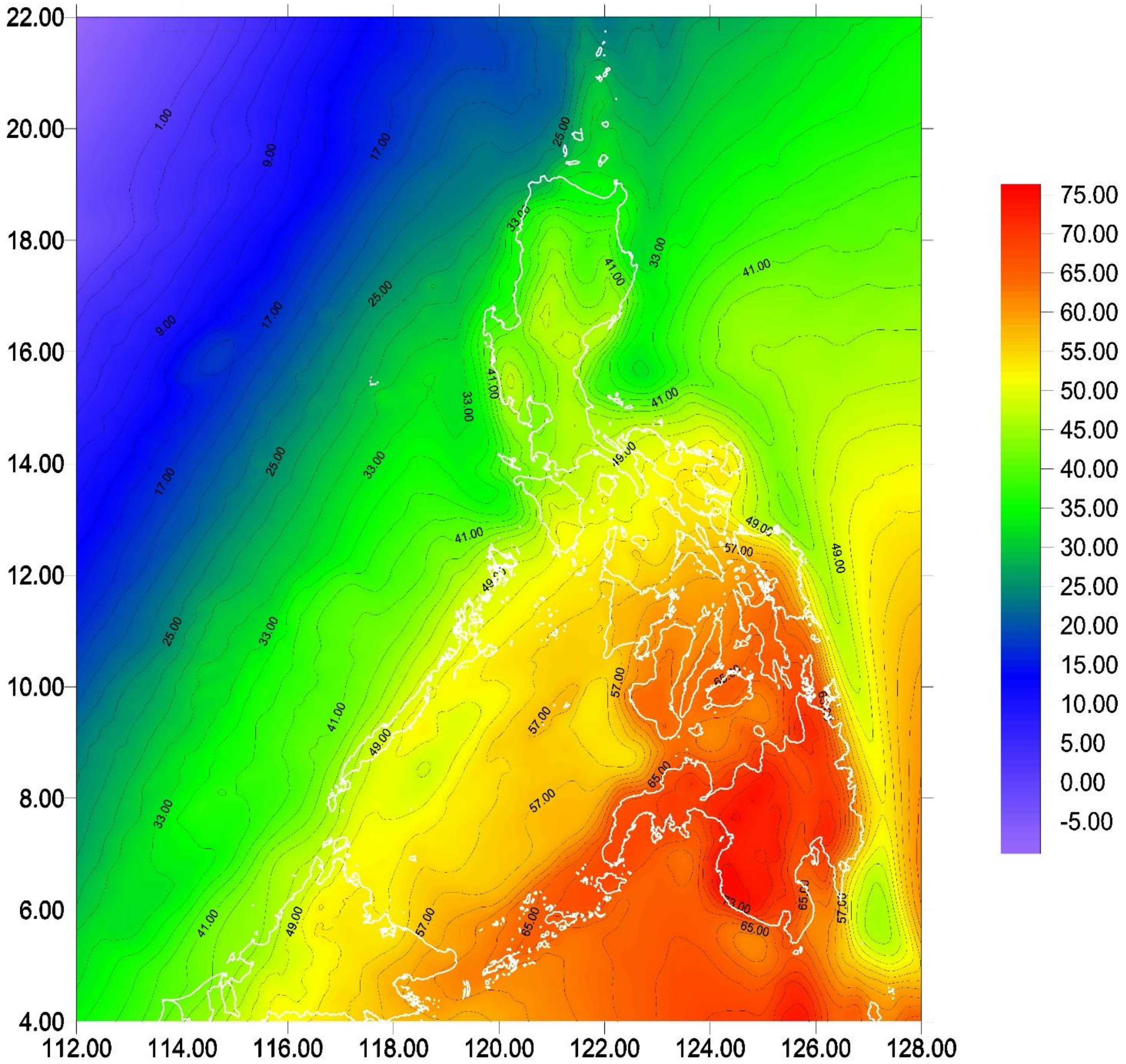


*Figure 11. The new PGM2018 with contour interval 2m*

## Conclusion

The computation and re-computation of the Philippine Geoid Model has been described, from the preliminary PGM2014 model, its re-computation to PGM2016, and then to the present PGM2018. The nominal accuracy of the PGM2018 is about 3 cm (after the fit to GNSS/levelling). To preserve the existing vertical reference datum of the topographic maps, the computed geoid was reduced to the benchmark ML-3 reference level surface to roughly fit the geoid in Metro Manila area. Then, in order to close the gap between the MSLs and the geoid, and fit the latter to the different MSL reference level surfaces of the islands in the country, (which in effect unifies them into an equipotential surface) Tidal Benchmarks (TGBMs) and BMs nationwide were surveyed by GNSS. The Standard Deviation of the fit is about 2cm. For GNSS survey projects requiring elevation accuracies of about 5 to 30 cm, the geoid model is a good alternative to geodetic leveling. The resulting H can only be as accurate as the geoid model and the GNSS surveys, thus, the following should be noted:

1. 3D coordinates of Ground Control Points changes with time due to advancement in GNSS technology and crustal deformation
2. Ellipsoidal heights must be accurate, acquired and computed in about the same epoch as the GNSS/Leveling (2010 or later); if not, use a vertical deformation model to bring the coordinates to the correct epoch
3. If there is no vertical deformation model, obtain the updated coordinates by connecting to an updated (re-observed) geodetic control

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